NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

TECHNICAL NOTE 3302

LIQUEFACTION OF AIR IN THE LANGLEY 11-INCH HYPERSONIC TUNNEL

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SUMMARY

Pressure and scattered-light measurements were made in the Langley 11-inch hypersonic tunnel to determine the effect of stagnation temperature on the flow in two Mach number 7 nozzles and to determine the nature of the condensation process occurring at low stagnation temperatures. Liquefaction of the air occurred very close to the saturation point without a condensation shock, a result which indicated that liquefaction took place on foreign nuclei such as water and carbon-dioxide particles. The results from varying the water vapor and carbon-dioxide content, however, could not be correlated with Max Volmer's condensation theory. The average particle radius was 480 angstroms in the test section of the single-step Mach number 7 nozzle for stagnation conditions of about 530° R and 29 atmospheres. Under these conditions, about 10^{10} particles per cubic centimeter were present.

INTRODUCTION

The earliest investigations of condensation phenomena in high-speed nozzles were concerned with the condensation of water vapor in a steam jet. The work in reference 1, together with later work on the expansion of humid air in supersonic nozzles, was explained on a quantitative basis by Oswatitsch (ref. 2). In either case, the gas expanded until the water vapor reached a supersaturation of about 4; then the static pressure increased sharply to a peak value after which it decreased as a result of further expansion of the gas. Oswatitsch's calculations show that condensation on fixed centers such as dust particles would have a negligible effect on the flow because of the relatively small population density of these particles and the slow rate of growth of droplets formed on them. Since the vapor pressure from the surface of extremely small droplets is much higher than that from a plane surface, some degree of supersaturation must be expected before droplets formed by random fluctuations in the density of the vapor can survive. The formula for the rate of formation of these particles due to statistical fluctuations for a gas in equilibrium as determined by Becker and Döring (ref. 3) shows

this process to be principally a function of the supersaturation of the vapor with a rapid rise above a certain value of the supersaturation.

In a steam jet, the rapid formation of a large number of these centers releases a sufficient amount of heat energy to cause a sharp rise in pressure. The station at which condensation is initiated can be predicted with a fair degree of accuracy for the steam jet and for a high Mach number air jet with a moderate amount of water vapor present. For expansion of air in a high Mach number jet when the moisture content is very low, much larger supersaturation values for water have been observed than in the simple case of steam. In a thesis by Head (ref. 4), the available data are reviewed with proposed modifications in the theory. It would appear that the theory developed for condensation of a homogeneous gas would have to be greatly modified to apply to the case of condensation of gas when that gas appears as a slight impurity in a noncondensable gas.

The expansion of dry air in a hypersonic jet was expected to behave in a manner similar to that of the steam jet (ref. 5). In this case, air would become supersaturated and, eventually, a sufficient number of centers would form to produce the characteristic rise in pressure. However, it was recognized that foreign centers such as carbon-dioxide particles or even ice particles might be formed and would tend to cause a decrease in the supersaturation of air (ref. 5). Tests at Princeton University (ref. 6) by Bogdonoff and Lees and at the Langley Aeronautical Laboratory (ref. 7) showed the absence of a sharp pressure rise (condensation shock) in hypersonic flow. Bogdonoff and Lees interpreted this result as an indication of the absence of condensation; whereas the Langley results showed the presence of condensation, first by the variation of pressures with tunnel stagnation temperature, and then by light scattering from the condensed particles. In reference 7 the absence of condensation shock was attributed to a gradual process of condensation, possibly on foreign nuclei such as carbon dioxide or water-vapor particles, rather than to spontaneous nucleation of air.

An attempt to eliminate the effects of carbon dioxide and water vapor on condensation of air was made by Stever and Rathbun (ref. 8). The partial pressures of these gases were reduced by a dry ice and alcohol trap. A degree of supersaturation was reported which was somewhat less than Volmer's equation predicted (ref. 9). However, the pressure measurements and scattered-light measurements may not accurately determine the initial point of condensation, although they definitely establish a limit in the downstream direction. The possibility that condensable impurities, although present in very small quantities, may have influenced the results is not excluded, but the conclusion is reached that condensation on nuclei of oxygen and nitrogen instead of impurities is also possible. Further attempts along this line of approach were made by Arthur and Nagamatsu (ref. 10) and Hansen and Nothwang (ref. 11). Both

these investigations used relatively pure nitrogen in small nozzles (1- and 1.4-square-inch test sections) and moderately low stagnation pressures for hypersonic-flow investigations (about 8 and 6 atmospheres, respectively). Arthur and Nagamatsu obtained from pressure measurements an estimated supercooling of about 32° F. This temperature increment was based on the point at which deviations in the pressures were noted. If small condensed particles were being formed earlier in the flow, this increment would no longer represent the amount of supercooling and may denote only the point at which the particles have become sufficiently large or numerous to cause a significant change in the measured pressures. For this case, the amount of supercooling would be somewhat less than the value indicated. Possible scale and pressure effects could reduce the degree of apparent supercooling in a larger nozzle operated at higher pressures. Arthur and Nagamatsu found that the amount of supercooling was decreased by increasing the amount of impurities such as water vapor, carbon dioxide, and to a lesser extent by oxygen. They concluded that spontaneous self-nucleation was not important for gases with the level of impurities of commercial nitrogen and that a new theory is required which includes the effects of impurities.

The present report summarizes the condensation work in the Langley 11-inch hypersonic tunnel and includes possible explanations of some of the discrepancies in published results. This investigation is a continuation of the work presented in reference 7 and includes the results of an investigation of condensation particle size and concentration determined by using scattered-light techniques in a nozzle designed for a Mach number of 7. Carbon-dioxide and water content, pressure, and temperature were varied in order to determine their effects on particle size and concentration.

SYMBOLS

I transmitted light signal without particles

I_1 scattered-light signal, $\theta = 30^\circ$

I_2 scattered-light signal, $\theta = 150^\circ$

ΔI transmitted-light-signal difference due to light scattered from particles

M Mach number

N number of condensed particles per unit volume

T_s	settling-chamber temperature
X	station along tunnel center line from nozzle throat
f	lens aperture
p_s	settling-chamber pressure
p_o	stream static pressure
p_i	measured impact pressure
p_w	wall static pressure
r	radius of condensed particles
θ	angle measured from incident light beam
ρ_o	stream density
ρ_{o_t}	stream density at test section

APPARATUS

The Langley 11-Inch Hypersonic Tunnel

The present investigation was conducted in the Langley 11-inch hypersonic tunnel over an extensive period of time and includes data obtained with both the two-step nozzle described in reference 12 and the single-step nozzle described in reference 13.

The tunnel is of the intermittent type with a closed system. The air flows from a high-pressure tank with a capacity of 400 cubic feet through a regulator valve, a storage heater, a control valve, the nozzle, and into a vacuum tank with a capacity of 12,000 cubic feet. The air is then pumped from the vacuum tank by means of a vacuum pump into a three-stage compressor. The compressor feeds the air at 50 atmospheres through an oil filter and a dryer. This pressure is maintained in the dryer by a check valve on the outlet side of the dryer. From the dryer the air is conducted to the high-pressure tank and stored at about 50 atmospheres. For the more recent tests on scattered light, the high-pressure-tank capacity was increased to 675 cubic feet and the vacuum capacity to 17,000 cubic feet.

The first step of the two-step nozzle expanded from a minimum section 1.500 inches high by 0.667 inch wide into a section 1.500 inches high by 9.950 inches wide. This step was designed to produce a uniform flow at a Mach number of 4.36. The second step was of constant width (9.950 inches), but the contoured upper and lower walls commenced with a sudden break of 10.25° to expand the height to 10.514 inches. The second step was designed as a minimum-length nozzle to reach a Mach number of 6.98 from the Mach number of 4.36 at the entrance of the second step. The length of the first step was 31 inches and the length of the second step was approximately 51 inches.

The single-step two-dimensional nozzle is described in reference 13 which gives its performance when the air was heated sufficiently to avoid saturation. The nozzle was a conventional two-dimensional nozzle having a minimum section 0.096 inch high by 9.95 inches wide. The design Mach number was 7.08 and the exit dimensions were 9.95 by 10.51 inches. The total length of the nozzle was approximately 48 inches.

Because of the extended duration of the investigation, the results have been obtained with (1) the original heater described in reference 12 with copper tubing as the heat reservoir and heat-transfer surface, (2) the heater replaced by a pipe, (3) the original heater (ref. 12) modified by replacing the copper tubing with steel tubing, (4) the original heater modified by a bypass line around it, and (5) a new heater containing non-scaling materials such as stainless steel, nickel, and nichrome. The contamination of the air with particles from the heater varied over a wide range for the various heater configurations used. Relatively large copper-oxide particles were released by the heater in the original configuration, whereas virtually no particles were emitted by the pipe that replaced the heater, by the heater bypass line, or by the new heater.

Pressure Instruments and Orifices

The pressure gages were of a diaphragm type which were developed for the Langley 11-inch hypersonic tunnel and are described in reference 12. The orifices were located along the center of the plane walls and were 0.025 inch in diameter. The time response of the pressure-measuring system was less than 10 seconds for a change in pressure from 2 inches of mercury to within 2 percent of a final constant value of 0.2 inch of mercury. This time response was adequate since the duration of the tests was longer than 30 seconds, and the lag was minimized by evacuating the nozzle and pressure instruments to less than 2 inches of mercury before a test. The static and impact probes used in this investigation are described in reference 13.

Scattered-Light Equipment

The scattered-light equipment, which was used to measure particle size, consisted essentially of a light source which produced a monochromatic beam of light and two multiplier phototube pickups placed at 30° and 150° to the light beam. This equipment is shown schematically in figure 1 and is described in reference 14. The amount of light received by the phototube was defined by a tube 1/2 inch in diameter and 6 inches long which was fastened to the light-tight housing containing the phototube. The pickups were alined to receive scattered light from a small area on the center line of the tunnel. The light received by the phototubes passed through a Polaroid film which cut out that component of the scattered light whose electric vector was perpendicular to the plane containing the light beam and the pickups. A small alternating-current argon lamp with a regulated alternating-current supply was used to calibrate the pickups.

Transmitted-Light Equipment

The determination of the concentration of the particles required a transmitted-light apparatus as well as the scattered-light apparatus. The equipment used to determine the percentage change of transmitted light consisted principally of a small monochromatic beam of light and a multiplier phototube. The light was supplied by a small incandescent lamp operated from a regulated supply. The other components are shown in figure 2. The light beam passed through a filter which passed a narrow band in the neighborhood of 5,500 angstroms wavelength. A second filter in front of the phototube cut out stray light from the blue light beam used in the scattered-light measurements. The direct-current signal from the phototube was fed through an amplifier into a recorder. In order to record the small difference in signal, a constant direct-current bias supply was used to subtract most of the signal so that the gain of the amplifier could be increased.

Traveling Scattered-Light Survey Equipment

A traveling photometer unit was used to detect particles farther upstream and to give an approximate determination of particle size at the early stations by measuring scattered light. A collimated beam of light about 1/4 by 3/4 inch was directed along the axis of the tunnel from the test section toward the minimum section. The scattered light was viewed by a recording photometer unit mounted on a moveable carriage. This unit, shown schematically in figure 3, consisted of two f/2.5 lenses of 7-inch focal length coupled together, a stop with a slot 1/32 by 1 inch, and a multiplier phototube. The output from the multiplier phototube went to a narrow-band alternating-current amplifier which fed into an aircraft

strip recorder. This arrangement permitted the 120-cycle signal from the alternating-current mercury-vapor lamp to be recorded with a minimum of background noise. This equipment could be used nearer the first minimum than could the other scattered-light equipment.

METHODS

Pressure Measurements

Pressure measurements were made on the center line of the plane walls of the two-step nozzle at various stations for a range of stagnation temperature from about 1,300° R to 540° R. During a test the temperature was held constant by the storage heater. The first test was made at the highest temperature. The temperature of the heater was then lowered by blowing down the high-pressure tank through the heater several times. Successive tests were made as the temperature of the heater was lowered in this manner.

The settling-chamber pressure ranged from 35 to 37 atmospheres for the two-step-nozzle tests. In reference 12 the Mach number in this nozzle was shown to remain constant for a change of pressure of this magnitude at temperatures above 1,100° R.

Similar pressure measurements on the plane wall were made on the single-step nozzle at a stagnation pressure of 29 atmospheres. Also, impact pressure and static-pressure measurements were made in the center of the stream in the test section.

The dewpoint was maintained below -60° F (21 parts of water per million parts of air by weight) at atmospheric pressure for this series of tests except in those tests in which the dewpoint was intentionally increased to study moisture effects. The moisture content was determined from measurements made with a Bureau of Mines dewpoint indicator. Measurements of the carbon-dioxide content were made for a few tests and it was found to be 0.013 percent by weight. Since the process of compressing the air has been found to reduce the carbon-dioxide content below the normal atmospheric value of 0.02 percent, the value of 0.013 percent has been assumed for all tests except those in which carbon dioxide was intentionally increased. The carbon-dioxide content was determined by precipitating the carbon dioxide from a given mass of gas in barium hydroxide and weighing the precipitate obtained.

Pressure measurements have been obtained with all the heater configurations previously mentioned and no difference has been detectable.

Scattered- and Transmitted-Light Measurements

To Determine Particle Size and Population Density

Measurements of scattered and transmitted light were made on the single-step nozzle. In order to obtain particle size and concentration under as nearly identical conditions as possible, the scattered- and transmitted-light measurements were obtained simultaneously. The green light beam used for the transmission measurements was located just below the blue light beam used for the scattering measurements. The equipment was calibrated before and after each test. The plane walls of the nozzle were made in sections so that windows could be placed at different intervals along the nozzle. The apparatus for measuring scattered and transmitted light was placed along the center line at the 55.81-, 36.7-, 13.34-, 11.9-, and 7.6-inch stations from the minimum section. The stagnation temperature was about 530° R for most of these tests. A few tests were made at elevated temperatures to determine the effect of temperature on particle formation in the region of the test section. The settling-chamber pressure for most of the tests was maintained at about 29 atmospheres. Several tests were made at different pressures to determine the effect of pressure on the population density and size of the particles in the region of the test section. Several runs were also made with carbon-dioxide content varied in order to determine its effect on the particles. The moisture content was also varied over a wide range to determine its effect on the particles.

The particle sizes and concentration were calculated from the scattered- and transmitted-light measurements as described in reference 14. For the particular wavelength, index of refraction, and incident angles used in this experiment, the radius in angstroms (A) can be obtained from figure 4. It should be mentioned that determination of the concentration of the particles is strongly dependent on the radius of the particles and, therefore, slight errors in radius can result in large errors in particle concentration. The results of these measurements are presented in tables I to III.

Measurement of Light Scattered From Light Beam at Axis of Tunnel

In order to obtain an indication of the particle size in the region of the single-step nozzle just downstream of the minimum section, the traveling scattered-light survey equipment was employed. Windows were placed just downstream of the minimum section, in the test section, and just upstream of the test section. These locations permitted observation of the scattered light from about the 1-inch station to the 6-inch station and at the 36.7-inch station.

The resolution of the photometer unit was checked by using it to scan a lighted plastic strip with scratches on it which was placed at a distance of 7 inches from the face of the first lens (the same location as the light beam during the tests). The scratches showed up as broad lines on the record and were compared with reference blips at 1-inch intervals. For the largest opening of the lens used (f/5.6 for one lens), the resolution was 1/12 inch, and for the smallest opening (f/16 for one lens), the resolution was 1/24 inch. This resolution was the limitation on the accuracy with which the station could be determined. The unit was installed at the window near the first minimum section and its position was determined by means of light reflected from a scratch on a plastic strip at a fixed station in the tunnel. The unit was driven back and forth across the windows twice for each run. Records were taken at different sensitivities in order to obtain a clearer indication of the initial point of condensation and the relative amount of scattered light at different stations. The sensitivities were changed by using various lens apertures and amplifier sensitivities. Typical records obtained by using this equipment at three sensitivities are shown in figure 5 for the traversing platform moving both upstream and downstream near the nozzle minimum section. The measurements and results obtained from these measurements are presented in table IV. This table contains estimated values of the particle size at several stations. Since the particles are about one-tenth the wavelength of light in radius, the scattered light is essentially Rayleigh scattering and, therefore, is proportional to the first power of the number of particles and to the sixth power of the particle size. On the assumption that the number of particles per unit mass of air is constant, the scattered light is proportional to the sixth power of the radius. Test results obtained at the 36.7-inch station, where the particle size was known from the scattered-light measurements (table I), were used to provide the proportionality factor.

RESULTS AND DISCUSSION

Static-Pressure Measurements

The results of the static-pressure measurements are presented in figures 6 to 9. The pressure measurements on the center lines of the plane walls of both nozzles show a smooth distribution in the region where a condensation shock might be expected to occur in the unheated condition. According to Charyk and Lees who used Volmer's theory (ref. 9), this condensation shock would be at about the 40-inch station on the two-step nozzle (fig. 6) and at about the 5-inch station on the single-step nozzle (fig. 8). The saturation point in the two-step nozzle is reached at a value of p_w/p_o of 0.0043 at about the 32-inch station; in the single-step nozzle the saturation point is reached at a value of p_w/p_o

of 0.0065 at the 1.4-inch station. (The values of the saturation points for air in this paper have been obtained by using ref. 15.) These pressure distributions are shown in figures 6 and 8, where the ratio of the static pressure to the settling-chamber pressure is plotted against the distance along the axis of the nozzle. The two-step nozzle (fig. 6) shows an apparent rise in pressure between the 28-inch station and the 31.14-inch station for both the heated and unheated conditions. However, the orifices are located in walls at right angles, the first being on the center line of the plane wall of the first step, and the second at the juncture between the contoured wall of the first step and the plane wall of the second step. Thus, they primarily show a difference in pressure across the flow rather than along the flow. In this nozzle, the first measuring station downstream of the saturation point (36.14-inch station) showed considerable change in pressure due to condensation (fig. 6). If the effect of condensation on the flow is neglected, the measured pressure at this point would indicate a temperature about 17° F below the condensation temperature. Since evidence of condensation is already present at this station, the degree of supercooling must be less than this value. In the single-step nozzle, differences in warpage of the nozzle between the 523° R and 1,282° R tests make a similar evaluation difficult, particularly near the minimum section (fig. 8). However, it is possible to fair the curves in figure 8 so that they do not deviate from each other significantly until about the 2- or 2.5-inch station. This result could be interpreted as showing that condensation did not occur until the 2- or 2.5-inch station (about 16° F to 20° F supercooling) or that the presence of condensation did not greatly affect the wall pressures. In any case, fairing the curves differently would not have increased the value of supercooling greatly.

In figures 7 and 9, the ratio of the wall static pressure to the settling-chamber pressure is plotted as a function of stagnation temperature at several fixed stations. The curves for the two-step nozzle (fig. 7) give practically constant values for the pressure ratio when the local static temperature is above the saturation temperature for air. At lower temperatures, the curves break suddenly, giving higher pressure ratios which indicate a lower Mach number. In each instance, the break occurs very close to the saturation temperature of air. The breaks in the curves for the single-step nozzle (fig. 9) are not so distinct because of a variation in the geometry of the throat with temperature. This variation shows up as a constant slope in the curve for local temperatures above the saturation temperature. Measurements were made of the distortion of the throat due to thermal stress in the nozzle blocks (ref. 13). By use of the dimensions of the throat and of the test section, the change in the measured Mach number for temperatures above the saturation point could be roughly predicted by the change in area ratio. Near the throat the effects could not be easily correlated since the flow near the wall experienced three-dimensional effects due to curvature of the throat in the transverse direction. The curves in figure 9 give a clear indication,

however, that a pronounced change in the flow takes place when the local static temperature drops below the saturation temperature for air. Curves of pressure against temperature for the single-step nozzle which have been obtained by using the various heater configurations are in agreement and indicate that the contamination of the air by particles from the heater has no influence on these curves. The pressure data on the plane wall of the single-step nozzle (figs. 8 and 9) were obtained with the new heater which incorporated only nonscaling materials.

Mach Number Effect

The Mach number for the flow in the test section of the single-step nozzle was determined at various temperatures in three different ways: by using the stream static pressure with the settling-chamber pressure, by using the measured impact pressure in the test section with the settling-chamber pressure, and by using the stream static pressure with the measured impact pressure in the test section. The results are presented in figure 10. The three methods give nearly the same value for isentropic flow and diverge for nonisentropic flow. Since the flow is not isentropic when condensation occurs, both Mach numbers calculated by using the settling-chamber pressure are obviously incorrect. The Mach number must, therefore, be calculated from local measurements. The Mach number calculated from the measured static and impact pressures in the test section will be most nearly correct. Further discussion of the determination of the Mach number in the presence of condensation is given in references 11 and 16. Figure 10, where the divergence occurs close to the saturation point, shows that, unless the stagnation temperature is maintained high enough to avoid supersaturation of the air, condensation will occur.

Particle Size and Concentration

Table I presents the particle size and concentration measured in the single-step nozzle at a stagnation pressure of 29 atmospheres and a stagnation temperature of 530° R. Results obtained at station 55.81 are included for two values of carbon-dioxide content. The maximum water content measured for these tests was 37 parts per million of air with most of the values below 10 parts per million. For a few tests, actual measurements of water content were not obtained and no value of water content is given; however, from measurements made for tests made just before and after these tests the moisture content could hardly have been greater than 6 parts per million for any of these tests. The average particle radius for each station from table I has been plotted against the nozzle station in figure 11. This figure shows that the principal growth of the particles in terms of radius occurs ahead of the 15-inch station and that in the test section the radius of the particles is about 480 angstroms; the concentration from table I is about 10^{10} particles per cubic centimeter. These results

also indicate that the number of particles increased slightly from the 13.34-inch station toward the test section. Upstream of the 13.34-inch station the small particle size causes very large errors in the interpretation of the results; the large and erratic values of N at the 7.6- and 11.9-inch stations in table I are, therefore, not considered significant. The increase in the number of particles per unit mass of air would be greater since the air density decreases in the downstream direction. The interpretation of the scattered-light measurements in terms of particle size and concentration is based on the assumption that the particles are spheres with an index of refraction of 1.20 and that they are nearly uniform in size. These conditions would be met if the condensation of air took place on foreign centers which were fixed in number at the saturation point of air and if the transition occurred from the vapor to the liquid phase. Under the conditions given for the scattered-light tests, the saturation point of air is reached at the 1.4-inch station at a Mach number of 4 with a static pressure of 0.19 atmospheres and a temperature of 126° R. Particles formed just downstream of this station would be liquid droplets. Even though the temperature of these droplets as they pass downstream may drop sufficiently to form solid particles, they may still exist as liquid droplets in a supercooled state, or if they become solidified they should still retain their spherical shape. The value of the index of refraction could vary appreciably and yet have only a slight effect on the calculated value of the radius as brought out in reference 14. If the particles are not uniform as assumed, then the calculated values of the radius are average values but considerable error may exist in the values of the concentration. However, if the distribution of size is fixed, indicated trends in concentration would be reliable.

No appreciable change in either radius or concentration was apparent at the test station (table I) when the carbon-dioxide content was increased from 0.013 to 0.032 percent. The increase of the carbon-dioxide content by a factor of 2.5 would be expected to have a large effect on the particle concentration if the centers were formed solely by carbon dioxide, according to Volmer's theory (ref. 9) which when simplified becomes

$$J = ax^2 e^{-\frac{b}{(\log_e x)^2}}$$

where x is the ratio of the partial pressure of the gas under consideration to its vapor pressure, and a and b are constants of the gas for a given temperature. An increase in x would cause the value of J (the number of particles formed per unit volume per second) to increase because of both the exponential term and its coefficient. If the change in the exponential is ignored, J would be proportional to x^2. The

effect of the exponent is dependent on the range of x considered and is, therefore, difficult to evaluate; however, in all cases it increases the variation of J with x. An increase in x by a factor of 2.5 would thus change J by a factor of at least 6.25. The fact that the variation with carbon dioxide was within the experimental scatter indicates either that Volmer's theory is not applicable or that carbon dioxide is not the major source of centers.

Water vapor may serve as another possible source of centers. Even though the moisture content was only a few parts per million in most of the tests, the saturation point of water occurs earlier in the nozzle than that of carbon dioxide. The results of varying the moisture content by a factor of over 500 to 1 are presented in table II. No systematic change in the radius is apparent within the accuracy of the data. A small increase in $\Delta I/I$ occurs for a large increase in the moisture content. If water were the only source of nuclei formation, Volmer's theory would predict an increase of at least 250,000 times the number of particles. It would appear from these results that the process of condensation nuclei formation is not one in which Volmer's theory can be applied.

In table III the radius of the particles can be seen to decrease as the temperature is increased or the pressure is decreased. This reduction in size with pressure would greatly increase the difficulties in making such tests at lower pressures than the pressure used in this investigation. Reducing the pressure from 586 to 211 lb/sq in. decreased the number of particles by a factor of about 6. Measurements on particle concentration as a function of temperature were subject to large errors because of the small radius of the particles, which approached the limit of accuracy of the equipment.

As stated previously, the reduced particle size at the upstream station limited the use of the scattered-light equipment at stations upstream of the 7.6-inch station. A different scattered-light technique described previously as the traveling scattered-light survey equipment was used. In order to obtain an apparent or approximate size for the particles, the number of particles per unit mass of gas was assumed constant. Since the scattered light is proportional to Nr^6, a large error in N causes a considerably smaller error in particle size. The estimated values from this survey are given in table IV and plotted in figure 12. The data from figures 11 and 12 cannot be faired into one continuous curve since the absolute values presented in figure 12 are only approximate and intended primarily to show the downward trend of the size of the particles as the saturation point is approached from the downstream side. Some of the discrepancy between the particle sizes in these two figures may also be caused by inaccuracies in measuring the sizes below about 400 angstroms in radius by the method used in obtaining the data for figure 12. The system using the traveling scattered-light equipment was not sensitive to particles with an apparent radius below about 200 angstroms.

The apparent particle radius was below this value forward of the 2-inch station. The supersaturation would be about 16° F if this station were the beginning of condensation. This value is about the same supersaturation that Stever and Rathbun (ref. 8) reported from the results of their scattered-light work, in which they assumed that particles were not present before being observed by light scattering. However, such scattered-light technique can establish only that the particles have reached a substantial size and cannot be used to detect the actual start of particle growth. Examination of the photometer records in figure 5 shows, as would be expected, that with increased sensitivity of the system (decreased f number or increased instrument sensitivity) the point at which the initial deflection first appears occurs farther upstream. It is difficult to determine from extrapolation of figure 12 how close to the saturation point (the 1.4-inch station) the particle growth started, but it seems clear that particles were present in this investigation considerably upstream of the 2-inch station.

General Discussion

The pressure measurements from the tests described in this report show that condensation under the given conditions is a gradual process unaccompanied by a condensation shock. The sudden change in the pressure ratio as the stagnation temperature is varied in the two-step nozzle shows that the process of condensation starts very close to the saturation conditions for air (fig. 7). This variation did not show up as clearly in the single-step nozzle (fig. 9), partly because of warpage at the throat; however, the scattered-light tests in the single-step nozzle show the existence of condensed particles which must have originated near the station at which saturation occurred. As pointed out for water vapor in the "Introduction," this gradual process of condensation starting near the saturation point for air is contrary to experience with condensation of pure vapors and indicates that foreign nuclei probably are present as nuclei for condensation of air. Possible foreign nuclei include condensable vapors of carbon dioxide and water and fixed particles such as dust. The high concentration of condensed particles as measured from the scattered-light tests makes remote the possibility of dust particles acting as centers for condensation. The improbability of dust particles acting as centers is also shown by the variation of concentration with pressure and temperature. If the nuclei were dust particles, the variation should be approximately linear with density, but the tests indicate otherwise. These tests then point to carbon dioxide and water as the principal source of nuclei. The tests in which the amount of these gases was varied showed negligible effect on the size and concentration of particles in the test section. Hansen and Nothwang (ref. 11) also noted this effect for carbon dioxide from simple scattered-light observations. On the other hand, the application of Volmer's theory in this case would show very large changes in the concentration of particles. Since a large change in concentration

of particles did not take place for this change in concentration of either gas, the process of formation of condensation nuclei must differ greatly from that predicted by Volmer's theory.

The results of Arthur and Nagamatsu (ref. 10) also show that, for changes in concentration of the carbon dioxide, the net effect on the flow in the test section is negligible, but that upstream the point at which the flow deviates appreciably from the isentropic conditions shifts with concentration. It appears from these observations that condensation nuclei are formed by either carbon dioxide or water vapor or both beginning upstream of the saturation point of air. Downstream of the saturation point of air, condensation principally in the form of oxygen (see ref. 5 or 15) forms on these nuclei.

In the formation of nuclei, the time factor as well as concentration of foreign material which can form nuclei is important. The two-step nozzle had a comparatively long distance between the Mach number 1 and Mach number 4 stations so that nuclei of carbon dioxide and water vapor had a much longer time to form in the two-step nozzle than in the single-step nozzle. This longer time in the two-step nozzle could well be the cause of the more pronounced pressure break with temperature in that nozzle. This result would also imply a more pronounced effect in the Langley 11-inch hypersonic tunnel than would be observed in a small nozzle, particularly if such a nozzle were operated at a lower stagnation pressure.

CONCLUDING REMARKS

Pressure and scattered-light measurements in the Langley 11-inch hypersonic tunnel with various stagnation temperatures have shown that liquefaction of the air originates very close to the saturation point without a condensation shock. This result indicates that liquefaction took place on foreign nuclei such as water and carbon-dioxide particles. The results from varying the water vapor and carbon-dioxide content, however, could not be correlated with Max Volmer's condensation theory. The average particle radius was 480 angstroms in the test section of the single-step Mach number 7 nozzle for stagnation conditions of about 530° R and 29 atmospheres. Under these conditions about 10^{10} particles per cubic centimeter were present.

Langley Aeronautical Laboratory,
National Advisory Committee for Aeronautics,
Langley Field, Va., August 6, 1954.

REFERENCES

1. Von Helmholtz, R.: Untersuchungen über Dämpfe und Nebel, besonders über solche von Lösungen. Ann. d. Phys., Fünte Folge, Bd. 27, Heft 4, 1886, pp. 508-543.

2. Oswatitsch, Kl.: Condensation Phenomena in Supersonic Nozzles. R.T.P. Translation No. 1905, British Ministry of Aircraft Production. (From Z.a.M.M., vol. 22, no. 1, Feb. 1942, pp. 1-14.)

3. Becker, R., and Döring, W.: Kinetic Treatment of the Nucleation in Supersaturated Vapors. NACA TM 1374, 1954.

4. Head, Richard M.: Investigations of Spontaneous Condensation Phenomena. Ph.D. Thesis, C.I.T., 1949.

5. Charyk, Joseph V., and Lees, Lester: Condensation of the Components of Air in Supersonic Wind Tunnels. Rep. No. 127, Princeton Univ., Aero. Eng. Lab., Mar. 1, 1948.

6. Bogdonoff, Seymour M., and Lees, Lester: Study of the Condensation of the Components of Air in Supersonic Wind Tunnels. Part I. Absence of Condensation and Tentative Explanation. Rep. No. 146, Princeton Univ., Aero. Eng. Lab., May 25, 1949.

7. Becker, John V.: Results of Recent Hypersonic and Unsteady Flow Research at the Langley Aeronautical Laboratory. Jour. Appl. Phys., vol. 21, no. 7, July 1950, pp. 619-628.

8. Stever, H. Guyford, and Rathbun, Kenneth C.: Theoretical and Experimental Investigation of Condensation of Air in Hypersonic Wind Tunnels. NACA TN 2559, 1951.

9. Volmer, Max: Kinetik der Phasenbildung. Bd. IV of Die Chemische Reaktion, K. F. Bonhoeffer, ed., Theodor Steinkopff (Dresden & Leipzig), 1939.

10. Arthur, P. D., and Nagamatsu, H. T.: Effects of Impurities on the Supersaturation of Nitrogen in a Hypersonic Nozzle. Memo. No. 7 (Army Ord. Dept. Contract No. DA-04-495-Ord-19), GALCIT, Mar. 1, 1952.

11. Hansen, C. Frederick, and Nothwang, George J.: Condensation of Air in Supersonic Wind Tunnels and Its Effects on Flow About Models. NACA TN 2690, 1952.

12. McLellan, Charles H., Williams, Thomas W., and Bertram, Mitchel H.: Investigation of a Two-Step Nozzle in the Langley 11-Inch Hypersonic Tunnel. NACA TN 2171, 1950.

13. McLellan, Charles H., Williams, Thomas W., and Beckwith, Ivan E.: Investigation of the Flow Through a Single-Stage Two-Dimensional Nozzle in the Langley 11-Inch Hypersonic Tunnel. NACA TN 2223, 1950.

14. Durbin, Enoch J.: Optical Methods Involving Light Scattering for Measuring Size and Concentration of Condensation Particles in Supercooled Hypersonic Flow. NACA TN 2441, 1951.

15. Wagner, Carl: Berechnungen über die Möglichkeiten zur Erzielung hoher Machscher Zahlen in Windkanalversuchen. WVA Archiv Nr. A 3, Wasserbau-Versuchsanstalt (Darmstadt), Mar. 22, 1942.

16. Grey, J., and Nagamatsu, H. T.: The Effects of Air Condensation on Properties of Flow and Their Measurements in Hypersonic Wind Tunnels. Memo. No. 8 (Army Ord. Dept. Contract No. DA-04-495-Ord-19), GALCIT, June 15, 1952.

TABLE I

PARTICLE SIZE AND CONCENTRATION OF VARIOUS STATIONS OF SINGLE-STEP NOZZLE

[T_s = 530° R]

p_s, atm	Water, parts per million (a)	I_1	I_2	r, A	I	ΔI	ΔI/I	N, per cc
55.81-in. station; percent CO_2 by weight, 0.013								
28.9	1.4	79	120	506	75.5	3.1	0.041	74 × 10^8
28.9	1.4	84	126	500	84.1	3.6	.043	80
28.9	1.4	84.5	121	465	81.5	3.3	.040	120
28.9	2.1	76	109	472	80.0	3.8	.047	120
28.9	2.1	72	106	486	79.8	3.1	.039	88
55.81-in. station; percent CO_2 by weight, 0.032								
28.9	<1.0	56.5	81	465	73.9	2.8	.038	110
28.9	1.6	58	84	479	70.3	2.9	.041	100
28.9	1.6	55.5	78	452	69.4	2.5	.036	130
28.9	<4.4	48	70	479	69.1	2.7	.039	95
28.9	<4.4	49	72	486	68.0	3.3	.049	110
28.9	<1.0	57.5	81	462	65	2.6	.040	110
28.9	<1.0	58	81	458	65	2.9	.045	72
36.7-in. station; percent CO_2 by weight, 0.013								
28.9	----	154.0	216	459	93	3.25	.035	87
28.9	----	157.5	221	459	89	3.1	.035	87
28.6	----	156.3	216	449	86	2.7	.031	87.5
13.34-in. station; percent CO_2 by weight, 0.013								
28.6	37	61	88	478	65	1.7	.026	40
29.3	25	70	102	485	61	1.5	.025	35
28.6	25	66	94	471	60	1.45	.024	32
28.4	20	62	90	481	60.5	1.4	.023	32
28.2	20	62	89	474	60	1.4	.023	30
11.9-in. station; percent CO_2 by weight, 0.013								
28.9	----	73.3	95.5	408	55	.6	.011	53.7
28.6	----	74.8	99	420	53	.6	.011	44.7
28.8	----	79.4	96.5	354	51.2	.97	.019	214
28.2	----	71.8	88	361	49.6	.85	.017	172
28.6	<4	67.9	84.5	370	53.5	.82	.015	139
28.6	<4	73.4	93.2	390	50	.72	.014	95
7.6-in. station; percent CO_2 by weight, 0.013								
27.4	20	23	25.5	257	57	.6	.011	840
29.0	20	28.5	32	270	56	.7	.012	770
29.0	9	33	37	270	54	.6	.011	210
28.4	9	32	37	305	54	.6	.011	430
28.8	<9	36	40.5	270	54	.75	.014	550
28.9	<9	36	42	312	54	.7	.013	250

[a]By weight.

TABLE II

PARTICLE SIZE AND CONCENTRATION IN TEST SECTION OF SINGLE-STEP NOZZLE AT VARIOUS MOISTURE CONTENTS

[T_s = 530° R ± 10° R; percent CO_2 by weight, 0.013]

p_s, atm	Water, parts per million (a)	I_1	I_2	r, A	I	ΔI	ΔI/I	N, per cc
28.9	1	127	203	542	53	2.5	0.047	44 × 10^8
28.9	1	121	201	563	51.5	2.6	.050	38
28.3	2	110	189	581	61	3.3	.054	34
28.6	2	101	176	588	61	3.3	.054	32
28.6	1	153	231	508	61.3	3.2	.052	72
28.9	1	153	233	512	61.3	3.1	.051	67
28.8	570	167	244	487	90.3	7.6	.084	154
28.2	570	164	240	487	89.5	7.4	.083	151
28.8	443	139	222	542	92.4	6.5	.070	67
28.9	570	150	226	508	89.0	6.1	.069	96
28.9	570	148	230	524	87.0	5.8	.067	78
29.3	420	82.8	140	573	86.0	5.0	.058	40
29.1	420	88	142	546	83.5	4.8	.058	52
28.6	381	74	123	563	83.1	4.8	.058	43
28.6	381	72.9	118.5	554	83.2	4.6	.055	47
28.8	268	90.4	149	560	81.3	4.9	.060	47
28.6	268	93.5	150	542	81.1	4.5	.055	52
29.1	240	106	176	563	80.8	4.8	.059	45
28.9	240	109	175	546	80.3	4.2	.052	47
28.9	195	147	220	504	76.0	4.1	.054	78
28.9	195	146	220	508	76.0	4.1	.054	74
28.9	151	165	234	469	76.0	3.95	.052	116
28.9	151	168	236	459	77.5	4.35	.056	140
28.6	219	105	169.6	549	78.5	4.4	.056	48
28.6	219	109	164	504	78.0	4.4	.056	82
27.8	168	110	176	542	76	3.9	.051	48
27.8	240	123	198	546	74	4.1	.055	50
29.3	159	151	222	491	73	4.5	.062	106
28.6	159	137	216	536	73.5	4.5	.061	62
28.8	151	101	159	531	71	3.7	.052	55
28.8	175	106	168	536	69.5	3.5	.050	51
29.1	127	127	208	556	67.3	3.5	.052	42
28.8	127	127	205	545	67.2	3.5	.052	48
28.9	82	141.5	217	515	63.5	3.5	.055	70
28.9	82	154	222	478	63.5	3.4	.054	108
28.1	26	146	219	504	63.9	3.1	.049	70
28.6	23	150	224	499	63.0	3.2	.051	78

[a]By weight.

TABLE III

PARTICLE SIZE AND CONCENTRATION IN TEST SECTION OF SINGLE-STEP NOZZLE AT VARIOUS STAGNATION PRESSURES AND TEMPERATURES

[Percent CO_2 by weight, 0.013]

p_s, atm	T_s, °R	Water, parts per million (a)	I_1	I_2	r, A	I	ΔI	ΔI/I	N, per cc
39.9	530	<1	59	84	472	76	6.8	0.090	220 × 10^8
28.4	530	1	61	86	466	76	3.2	.042	120
20.4	530	1	22.5	30.5	438	73	1.3	.018	67
14.4	530	1.4	8.8	11.7	427	71	.56	.008	35
39.5	530	20	51	72	466	86	7.4	.086	240
28.4	530	17	48.5	64.8	431	82.3	3.4	.041	180
20.7	530	17	21	27.8	423	82.5	1.8	.022	98
14.7	530	17	7.3	9.6	417	80.5	.7	.009	52
28.9	1,070	20	3	.8	---	76	---	-----	---------
28.9	1,112	20	2	.6	---	75	---	-----	---------
28.9	1,073	20	4	.6	---	76	---	-----	---------
28.9	984	20	5	3.5	---	78	---	-----	---------
28.9	909	21	11	13	---	75	---	-----	---------
28.9	846	21	14	16.5	326	74	.3	.004	130
28.9	768	25	43	51	330	65	.5	.008	180
28.9	711	19	42	26.5	380	70	.5	.007	71
28.9	672	11	34.5	44	400	78	.85	.011	84

[a]By weight.

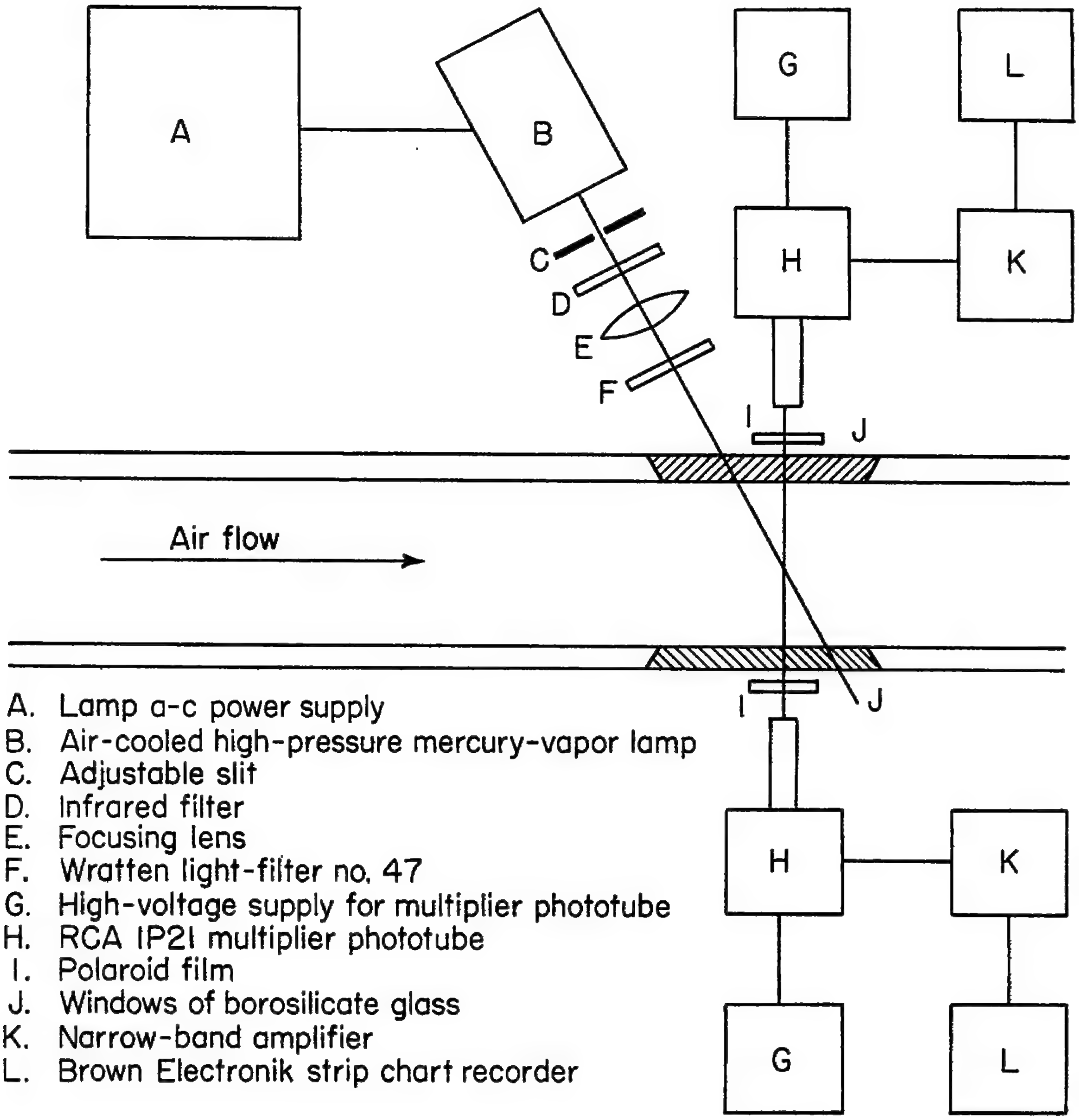
TABLE IV

APPARENT PARTICLE SIZE IN SINGLE-STEP NOZZLE FROM

TRAVELING SCATTERED-LIGHT SURVEY EQUIPMENT

$\left[p_s = 27.9 \text{ atm}; T_s = 530^\circ \text{ R} \pm 10^\circ \text{ R}\right]$

Station	Signal, millivolts	f	Effective signal, millivolts	ρ_{o_t}/ρ_o	Corrected effective signal	r, A
1.98	7.0	5.6	7.0	0.16	1.1	217
2.00	.9	16	7.3	.16	1.2	218
2.02	8.6	5.6	8.6	.16	1.4	227
2.13	3.3	16	27	.17	4.6	282
2.32	5.6	16	46	.19	8.5	308
2.36	32	5.6	32	.19	6.1	295
2.38	6.6	16	54	.19	10	320
2.62	41	5.6	41	.21	8.4	308
3.62	65	5.6	65	.27	18	352
3.62	9.4	16	76	.27	21	362
36.7	----	16	----	.98	----	---
36.7	85	5.6	85	.98	83	455



A. Lamp a-c power supply
B. Air-cooled high-pressure mercury-vapor lamp
C. Adjustable slit
D. Infrared filter
E. Focusing lens
F. Wratten light-filter no. 47
G. High-voltage supply for multiplier phototube
H. RCA IP21 multiplier phototube
I. Polaroid film
J. Windows of borosilicate glass
K. Narrow-band amplifier
L. Brown Electronik strip chart recorder

Figure 1.- Scattered-light equipment.

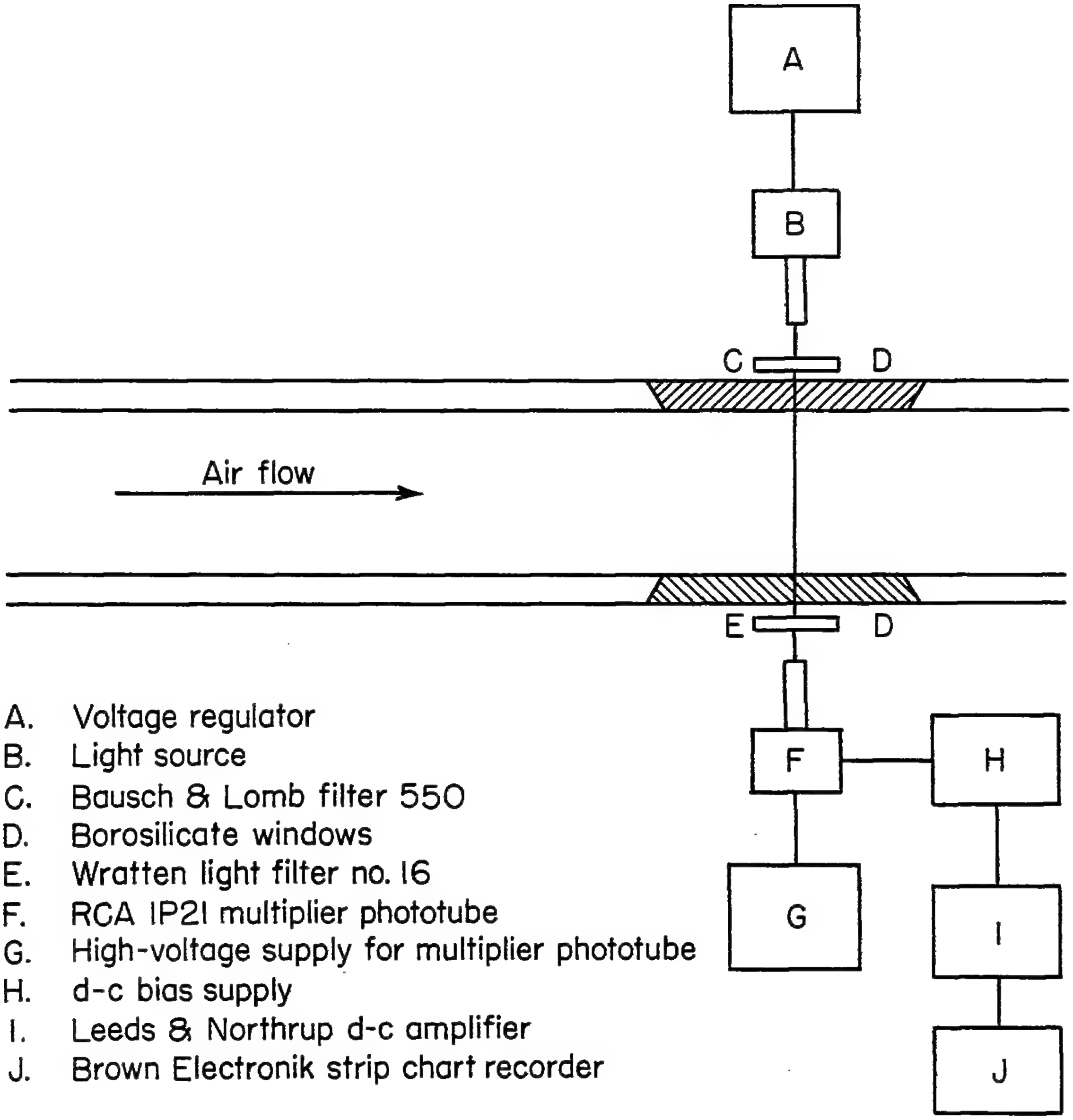
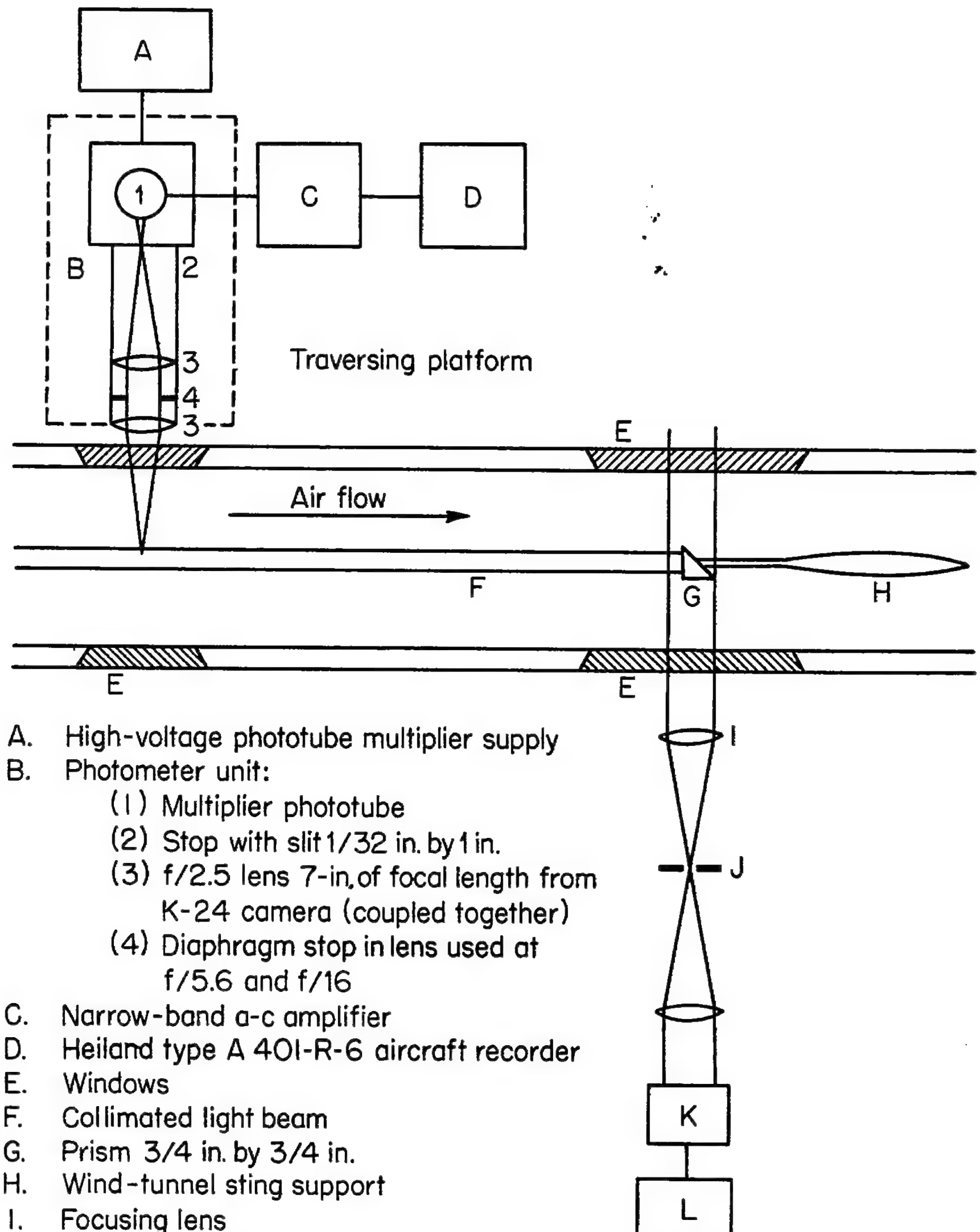


Figure 2.- Transmitted-light equipment.



A. High-voltage phototube multiplier supply
B. Photometer unit:
    (1) Multiplier phototube
    (2) Stop with slit 1/32 in. by 1 in.
    (3) f/2.5 lens 7-in. of focal length from K-24 camera (coupled together)
    (4) Diaphragm stop in lens used at f/5.6 and f/16
C. Narrow-band a-c amplifier
D. Heiland type A 401-R-6 aircraft recorder
E. Windows
F. Collimated light beam
G. Prism 3/4 in. by 3/4 in.
H. Wind-tunnel sting support
I. Focusing lens
J. Diaphragm with 1/8-in. hole
K. Air-cooled high-pressure mercury-vapor lamp
L. Lamp a-c power supply

Figure 3.- Traveling scattered-light survey equipment.

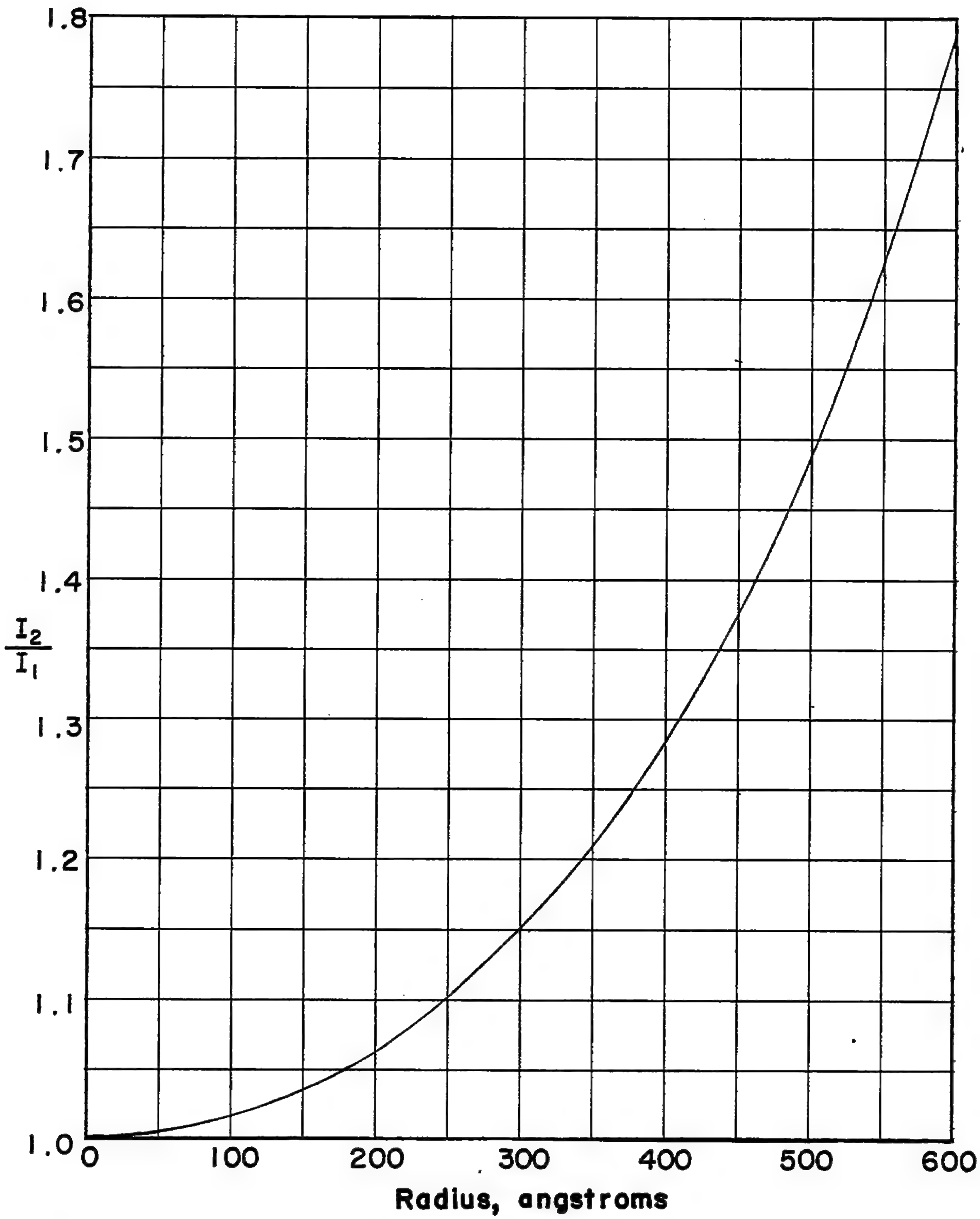
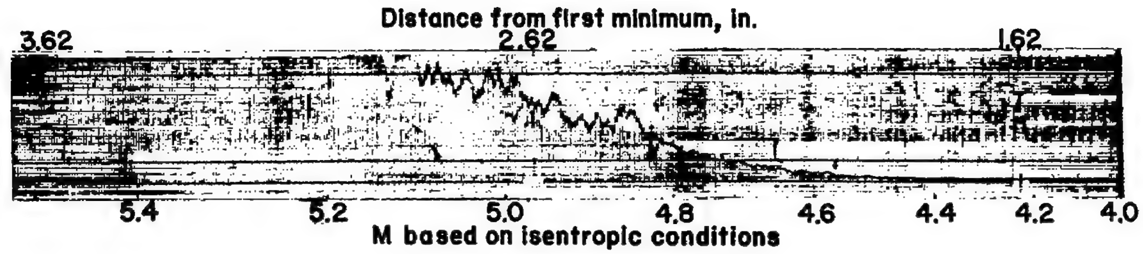
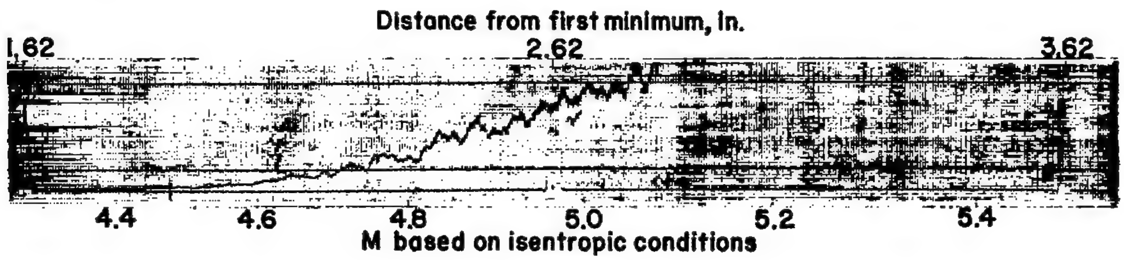


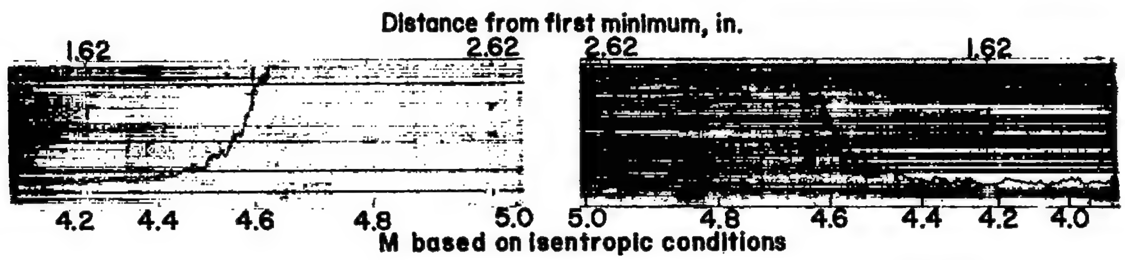
Figure 4.- Ratio of light scattered at 30° and 150° as a function of particle radius. Index of refraction, 1.20; wavelength, 4,358 angstroms.



(a) Moving downstream. Lens aperture, f/16; amplifier sensitivity, 1.

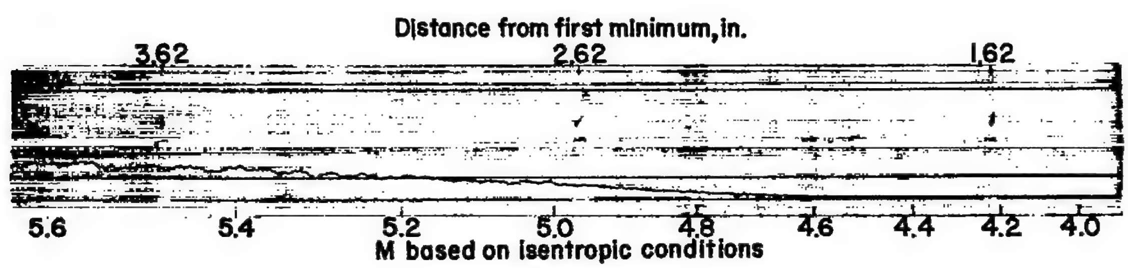


(b) Moving upstream. Lens aperture, f/16; amplifier sensitivity, 1.



(c) Moving upstream. Lens aperture, f/5.6; amplifier sensitivity, 1.

(d) Moving downstream. Lens aperture, f/5.6; amplifier sensitivity, 1.



(e) Moving downstream. Lens aperture, f/16; amplifier sensitivity, 0.1.

Figure 5.- Photometer records from traveling scattered-light survey equipment. p_s = 27.9 atmospheres; T_s = 530° R.

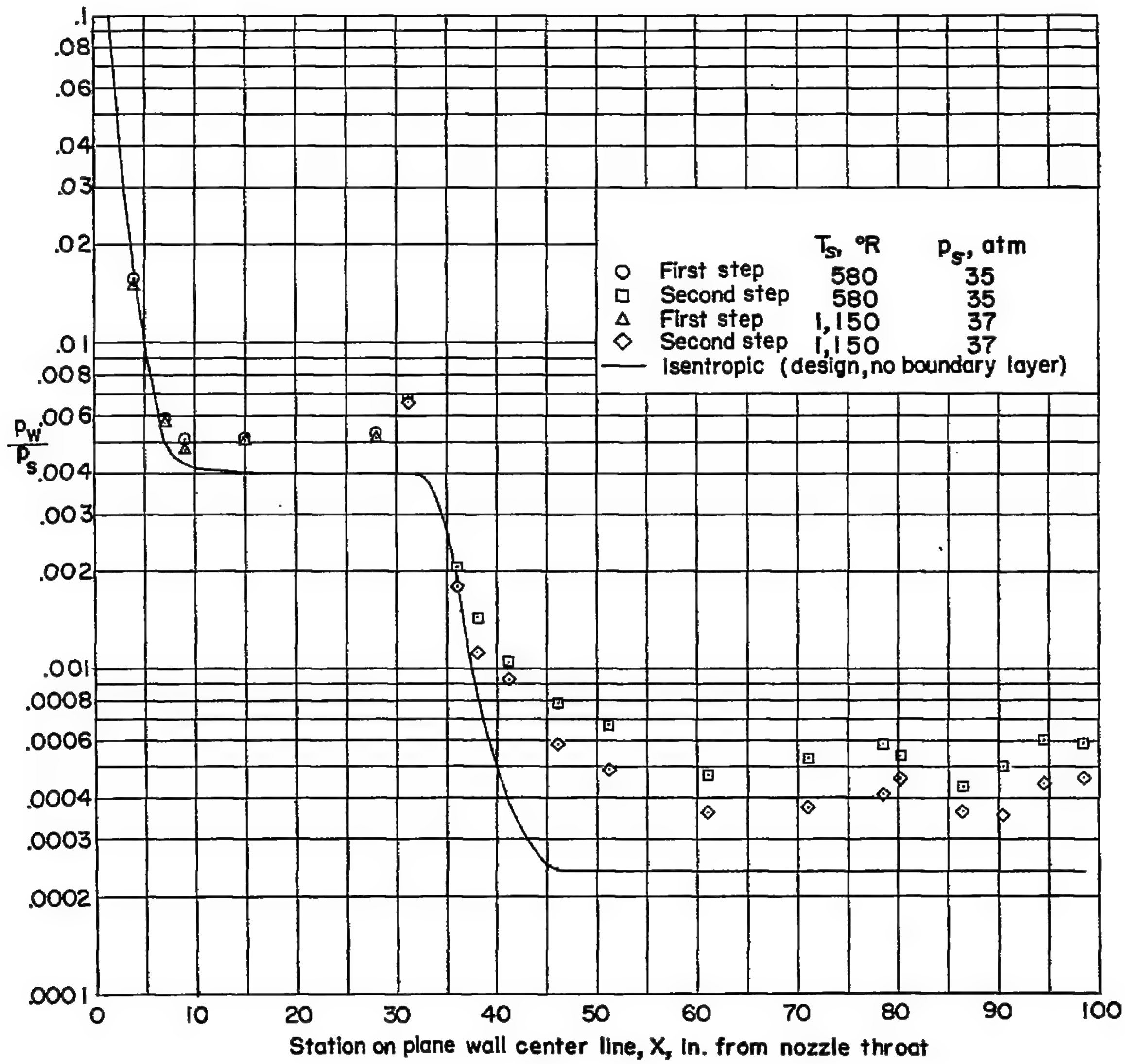
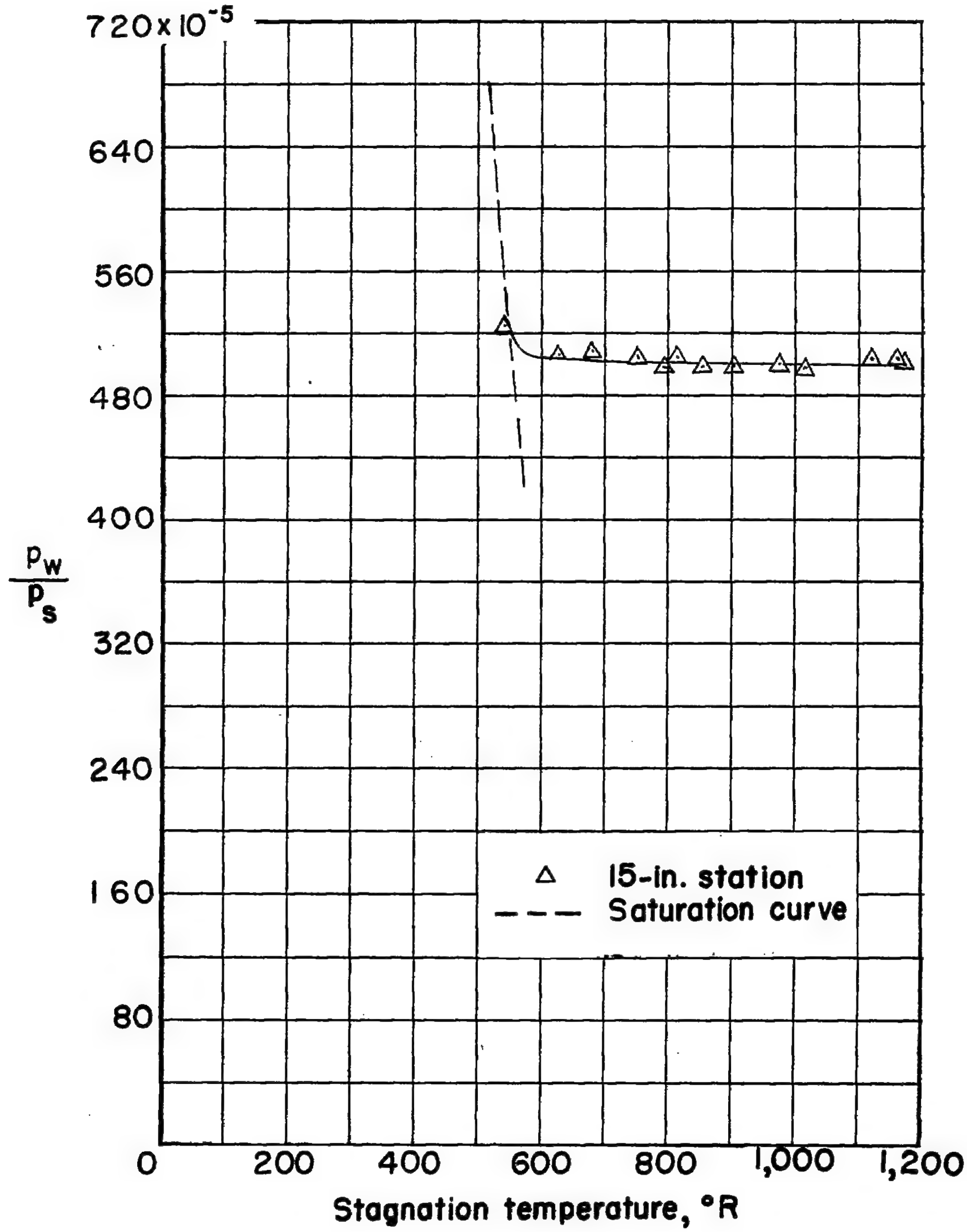
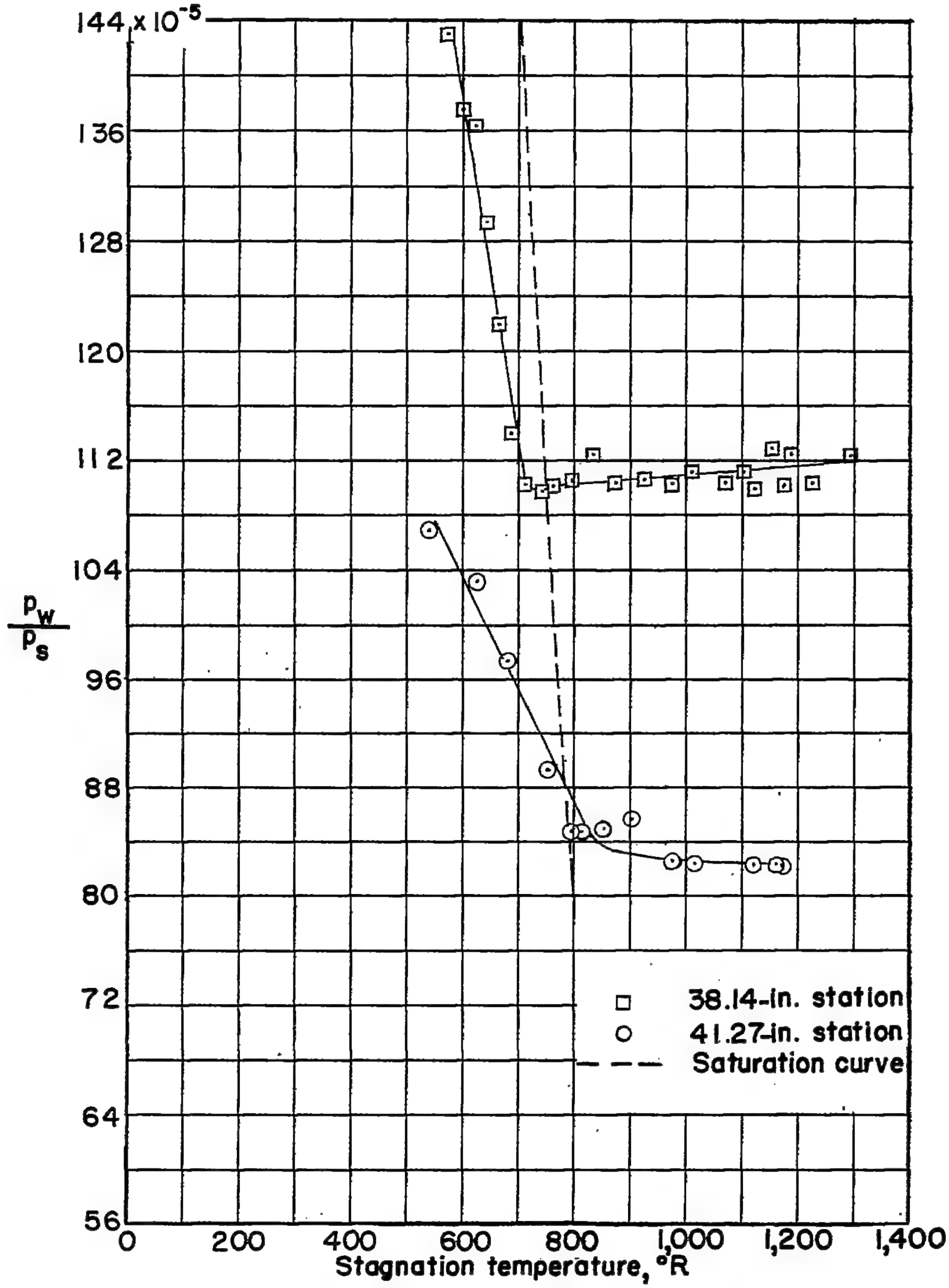


Figure 6.- Variation of static pressure along center line of plane walls of two-step nozzle.



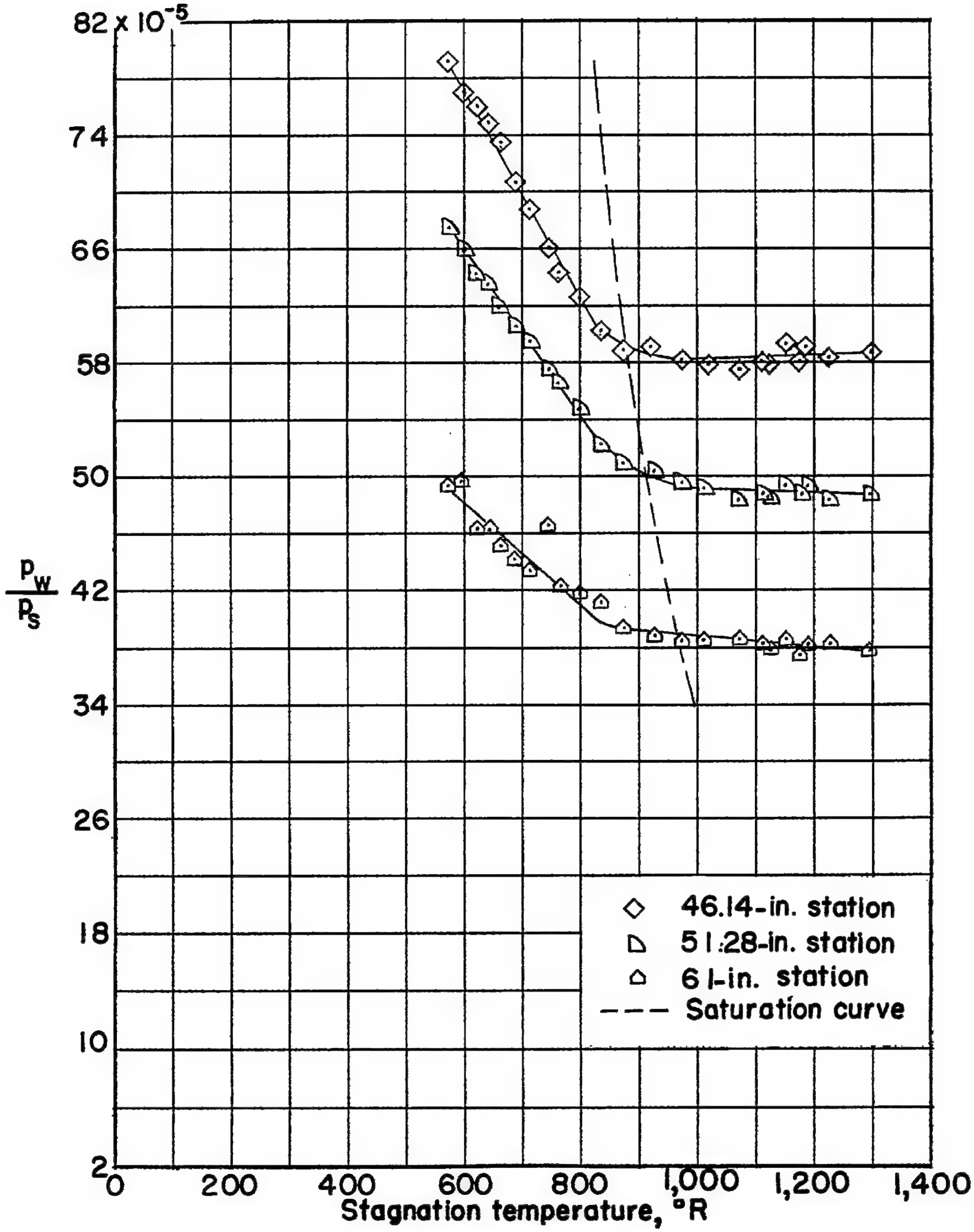
(a) 15-inch station.

Figure 7.- Effect of condensation on ratio of wall pressure to settling-chamber pressure in two-step nozzle. p_s = 35 to 37 atmospheres.



(b) 38.14- and 41.27-inch stations.

Figure 7.- Continued.



(c) 46.14-, 51.28-, and 61-inch stations.

Figure 7.- Concluded.

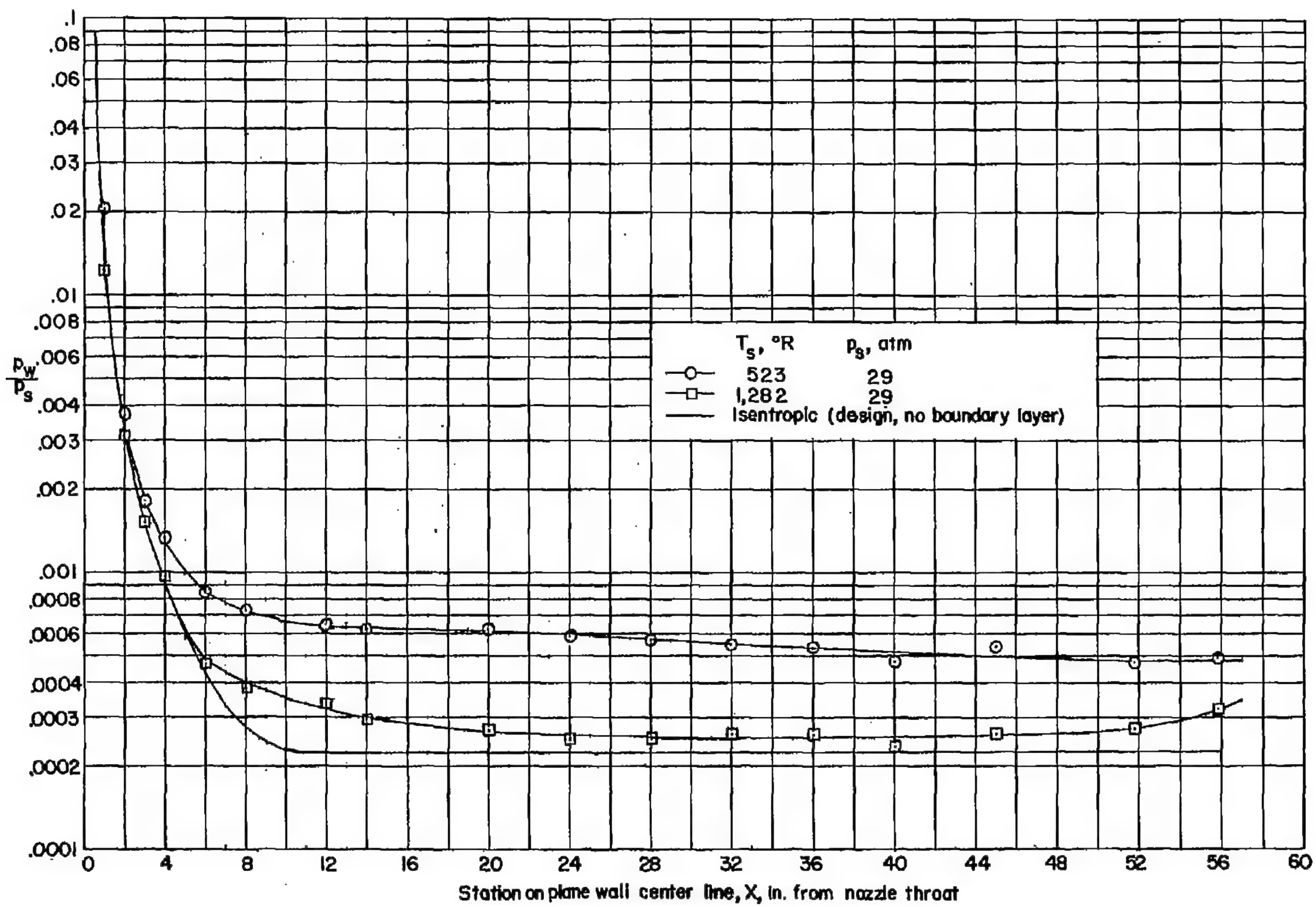
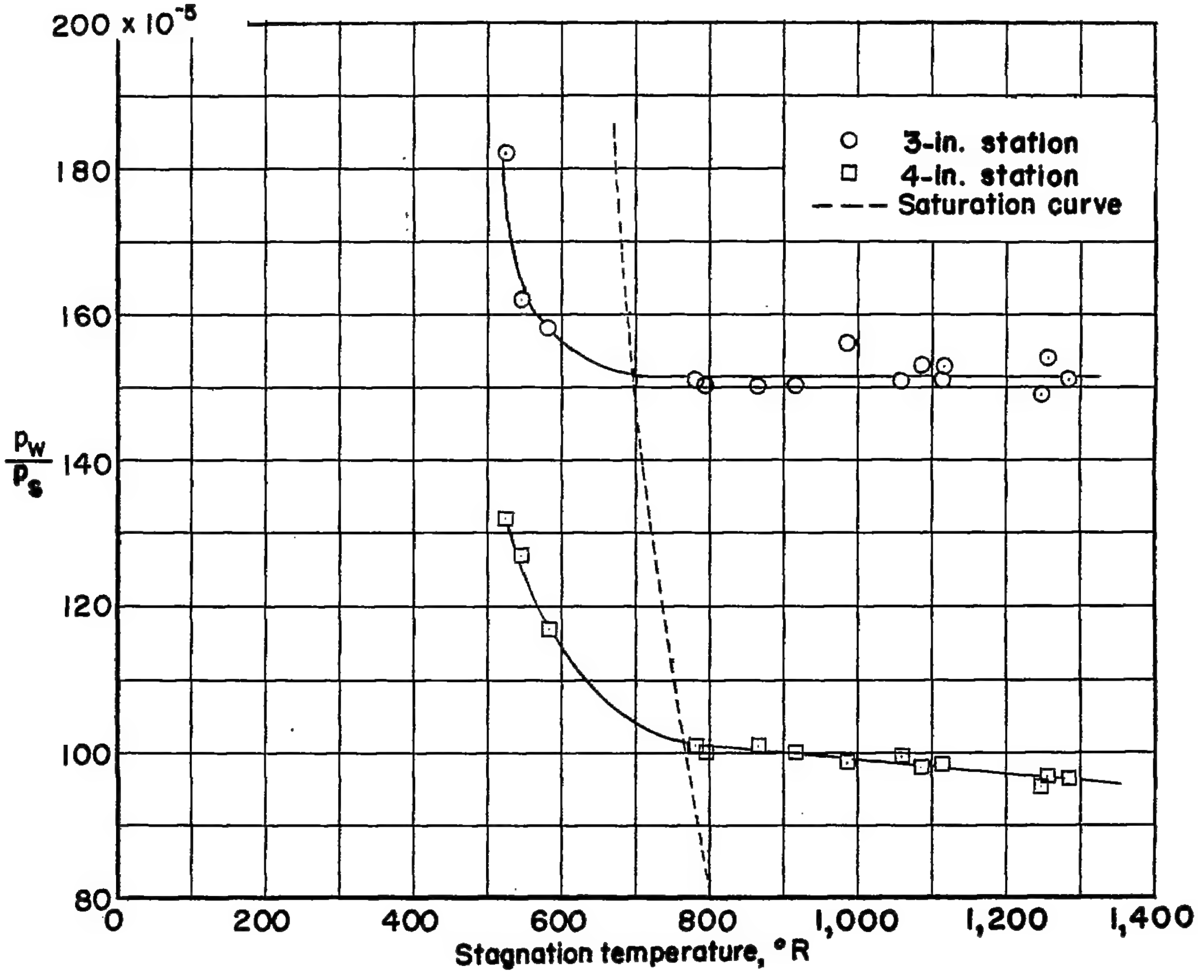
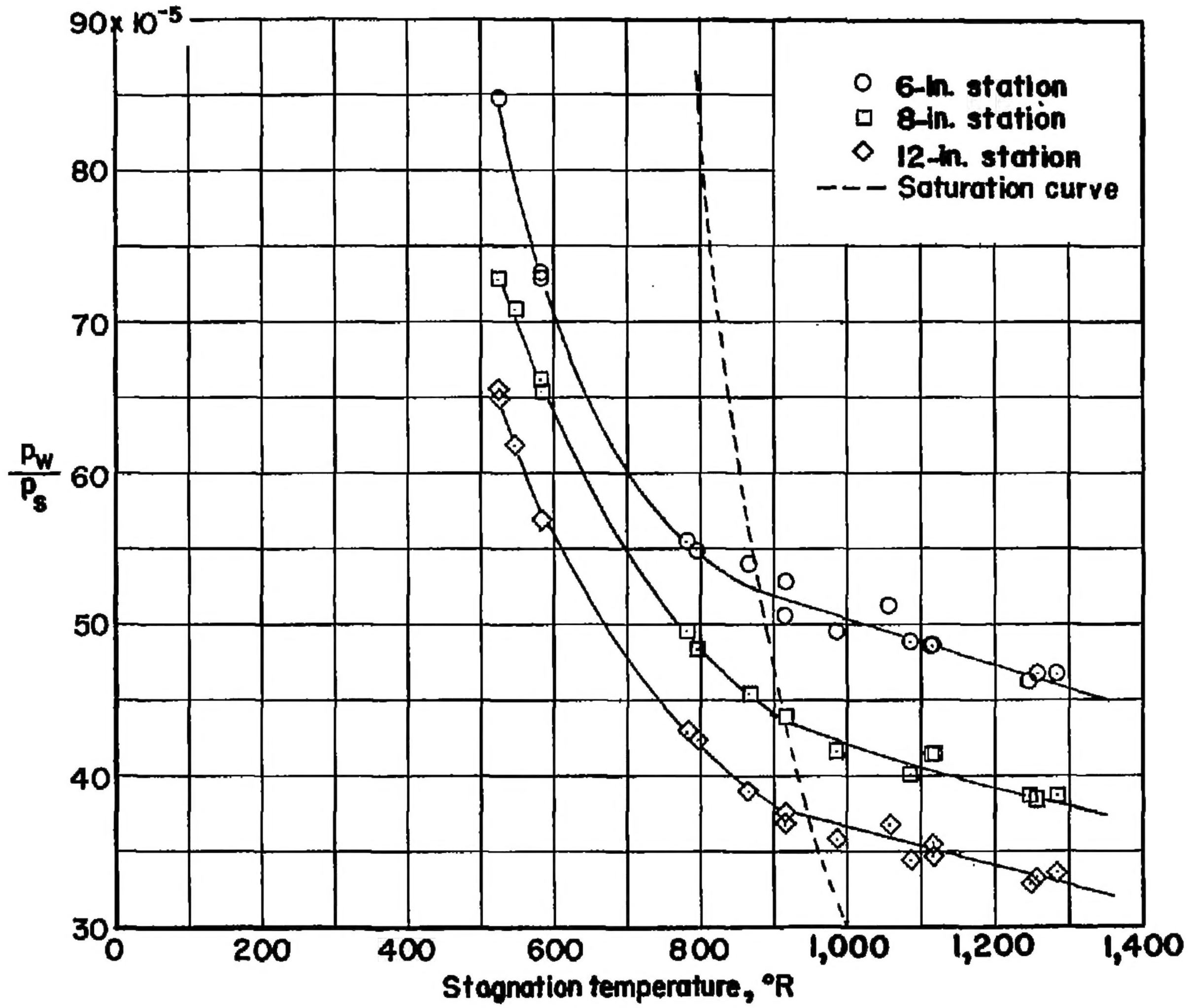


Figure 8.- Variation of static pressure along center line of plane wall of single-step nozzle.



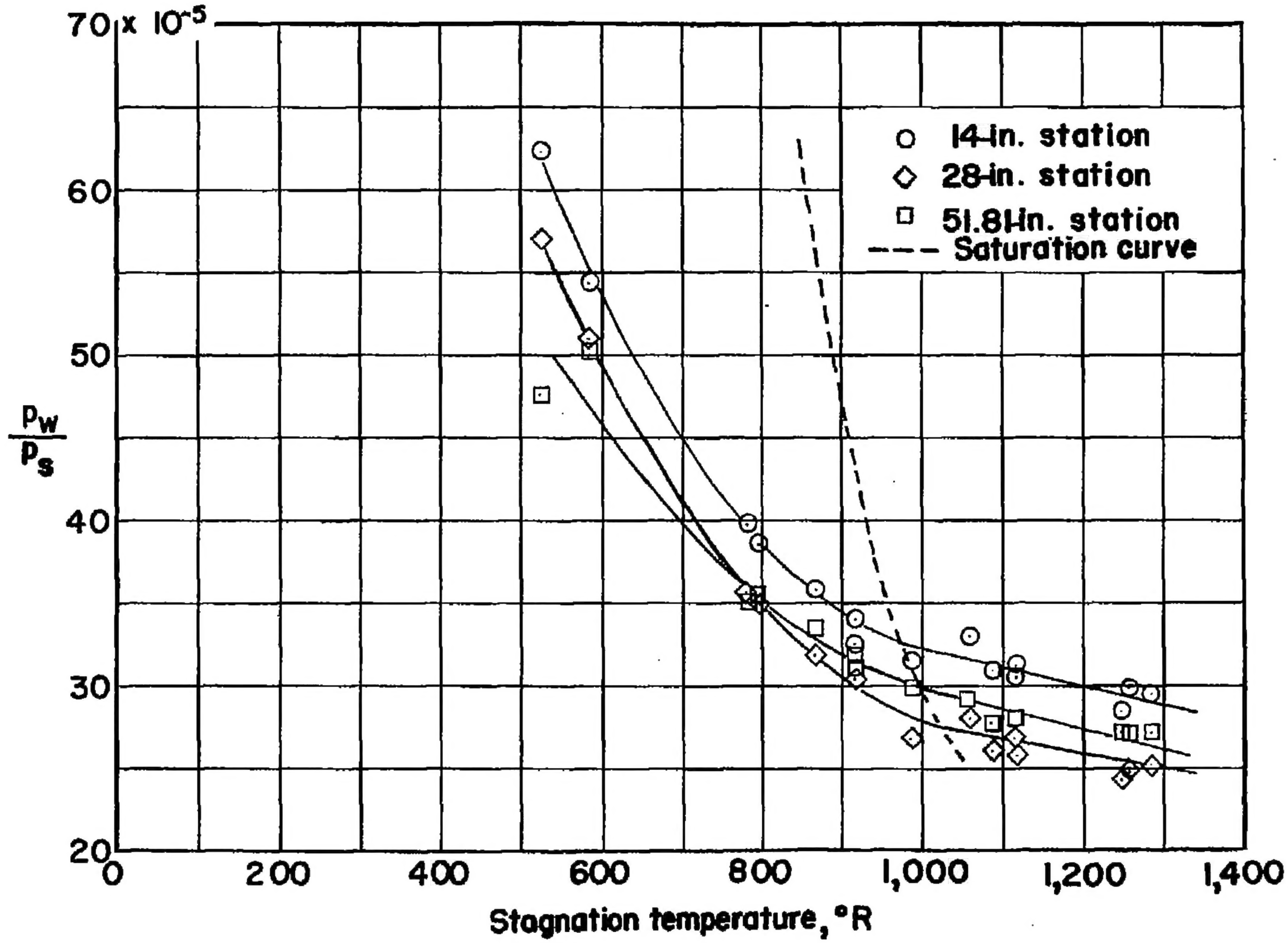
(a) 3- and 4-inch stations.

Figure 9.- Variation with stagnation temperature of static pressure on plane wall of single-step nozzle. p_s = 29 atmospheres.



(b) 6-, 8-, and 12-inch stations.

Figure 9.- Continued.



(c) 14-, 28-, and 51.81-inch stations.

Figure 9.- Concluded.

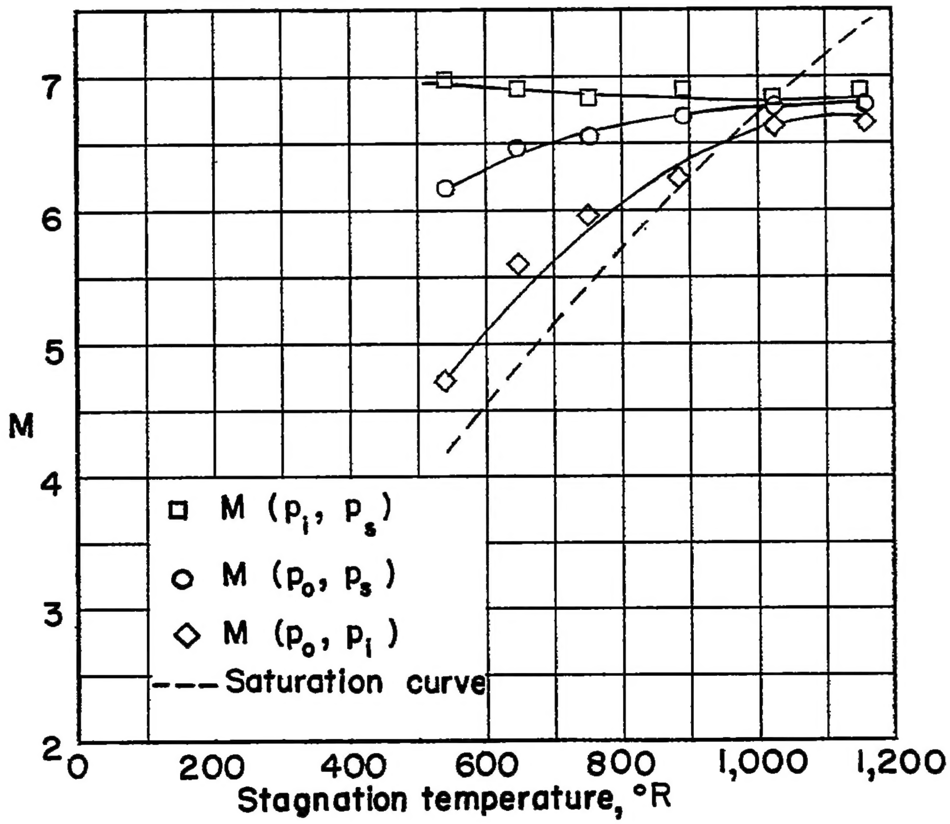


Figure 10.- Variation of Mach number with temperature in center of test section of single-step nozzle. p_s = 29 atmospheres.

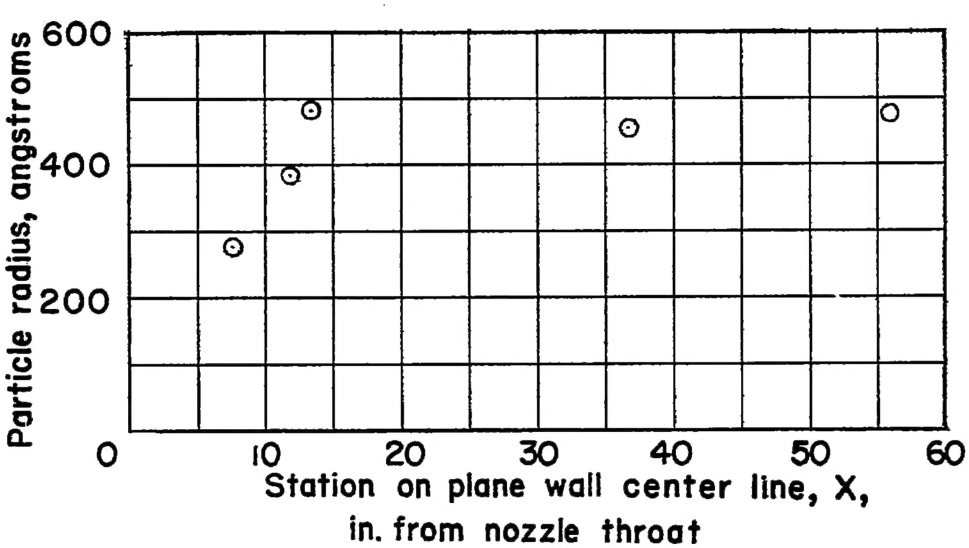


Figure 11.- Variation of particle size along single-step nozzle center line. p_s = 29 atmospheres; T_s = 530° R.

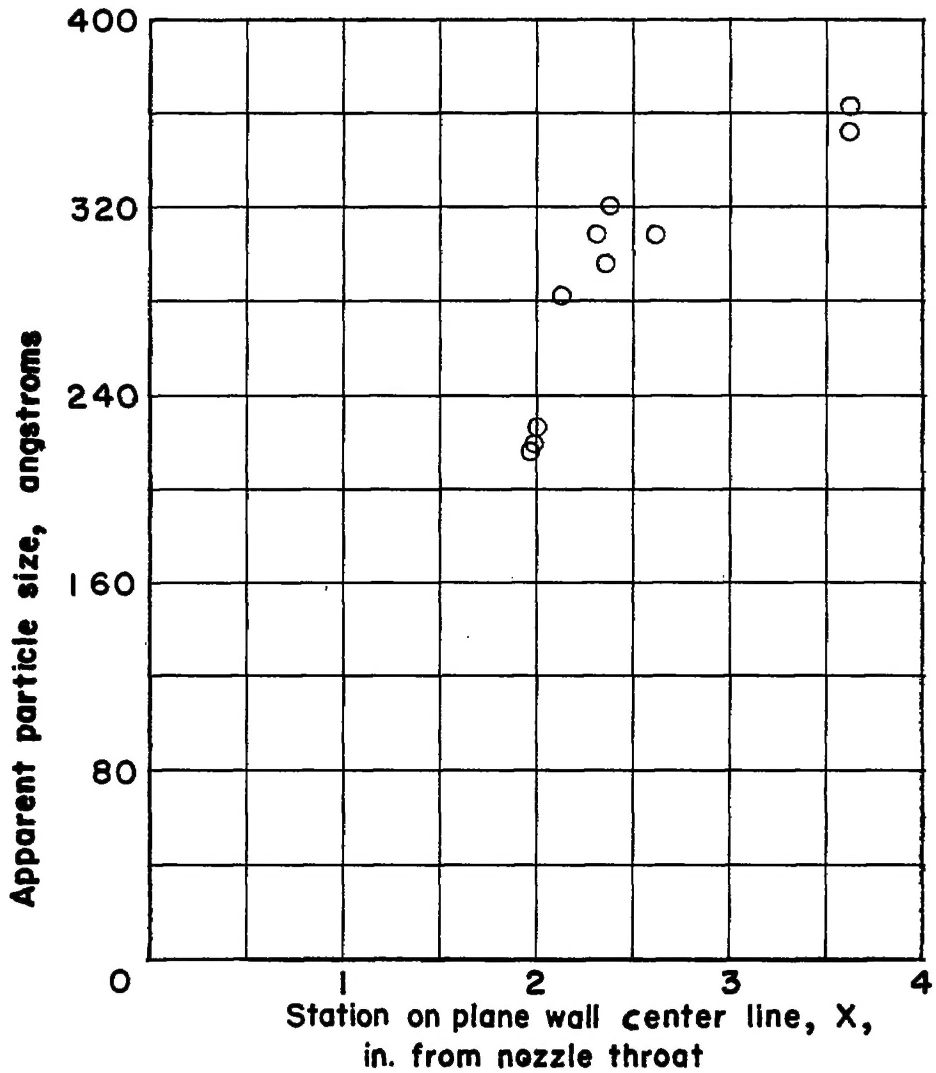


Figure 12.- Variation of apparent particle size along center line of single-step nozzle from traveling scattered-light survey equipment. p_s = 29 atmospheres; T_s = 530° R.